A LASER-TRIGGERED MINI-MARX FOR LOW-JITTER, HIGH-VOLTAGE APPLICATIONS

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Abstract

A relatively simple method for generating high-voltage (~200 kV) trigger pulses with low jitter (~1 ns) has been developed at the Nike KrF Laser Facility. The output pulse (~10 mJ) from a frequency-quadrupled Nd:YAG laser is focused between the electrodes of a spark gap, which acts as the first-stage switch in a compact, eight-stage Marx generator. The spark gap is pressurized with a mixture of sulfur hexafluoride and air. The UV (266 nm) laser energy ionizes the SF_6, creating a spark which triggers the switch. A 20-cm focal length lens is used. The defocusing laser light then illuminates the remaining, self-breaking spark-gap switches in the Marx, pre-ionizing them. The Marx output is approximately 200 kV into 50 ohms, with a risetime of 2 ns. A single Marx is capable of triggering six 100-kV spark gaps via six 65-ohm cables in parallel, with an overall jitter of ±1 ns. A single laser triggers three Marxes; the trigger timing of each can be adjusted independently by changing the laser path lengths. The system uses off-the-shelf components throughout.

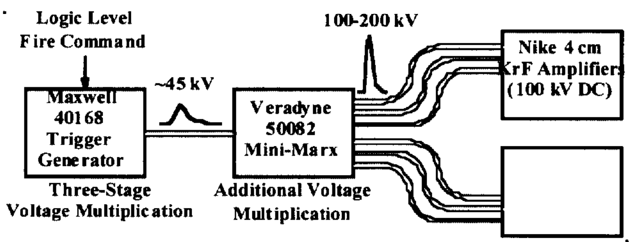

Figure 1. A conventional electrical trigger system using multiple stages of voltage multiplication.

I. HIGH VOLTAGE TRIGGERING

A common dilemma in pulsed power is that it requires high voltage to trigger high voltage. A conventional, all-electrical approach to triggering high-voltage spark gaps typically uses a series of voltage multiplication stages. An example of such a series was, until recently, used to trigger the 4-cm × 4-cm KrF laser amplifiers at the Nike Laser Facility (see Fig. 1). A low-voltage logic pulse triggered a Maxwell 40168 trigger amplifier. Within the Maxwell unit a solid-state amplifier gave a 500-V output pulse, triggering a thyratron at 12 kV, which triggered a spark gap to discharge a capacitor bank at 35 kV DC. This output discharge triggered a Veradyne 50082 mini-Marx generator, creating a fast-rising, 100–200-kV pulse, which triggered the three parallel, 100-kV spark gaps (Maxwell 40264) in each of the amplifiers. The stored energy in each amplifier was 25 J. While this system was reliable and easy to operate, the multiple switching stages led to an overall timing jitter ($\pm 2\sigma$) of ±4 ns between the logic-level command and the amplifier firing time. The Maxwell 40168 proved to be the largest single contributor to the jitter, followed by the Veradyne mini-Marx.

Laser-triggered spark gaps are capable of operating with very low jitter. The Nike laser, however, uses a total of five 4-cm × 4-cm amplifiers, each with three spark gaps in parallel. Laser triggering fifteen spark gaps in five different locations would be expensive and unwieldy, requiring a complex optical system and 150-200 mJ of UV energy from the trigger laser. A simpler approach is to use laser-triggered, high-voltage pulse generators capable of electrically triggering one or two amplifiers each.

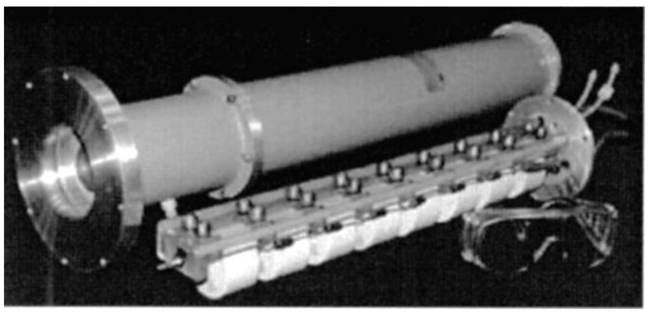

Figure 2. The Veradyne 50082 mini-Marx, invented by David Platts of Los Alamos National Laboratory.

The Veradyne mini-Marx (see Fig. 2) is adaptable to this task. Its output is over 200 kV into a 23 Ω load, with a risetime of less than 2 ns [1]. It has demonstrated the ability to trigger two Nike 4-cm × 4-cm amplifiers, with subnanosecond jitter between the Marx output and the amplifier outputs. The electrically triggered mini-Marx employs a trigatron spark gap as its first stage switch, with self-breaking spark gaps elsewhere [2]. It exhibits an overall jitter of ±1.5 ns between trigger input pulse and Marx output when triggered by a Maxwell 40168. This jitter was reduced by laser-triggering the first stage switch of the mini-Marx directly, an arrangement which also eliminated the Maxwell unit from the system. The laser-

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14. ABSTRACT
A relatively simple method for generating high-voltage (-200 kV) trigger pulses with low jitter (-1 ns) has been developed at the Nike KrF Laser Facility. The output pulse (-10 mJ) from a frequency-quadrupled Nd:YAG laser is focused between the electrodes of a spark gap, which acts as the first-stage switch in a compact, eightstage Marx generator. The spark gap is pressurized with a mixture of sulfur hexafluoride and air. The UV (266 nm) laser energy ionizes the SFs, creating a spark which triggers the switch. A 20-cm focal length lens is used. The defocusing laser light then illuminates the remaining, selfbreaking spark-gap switches in the Marx, pre-ionizing them. The Marx output is approximately 200 kV into 50 ohms, with a risetime of 2 ns. A single Marx is capable of triggering six lOO-kV spark gaps via six 65ohm cables in parallel, with an overall jitter of *I ns. A single laser triggers three Marxes; the trigger timing of each can be adjusted independently by changing the laser path lengths. The system uses off-the-shelf components throughout.

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triggered mini-Marx system currently fires the Nike 4-cm × 4-cm amplifiers with an overall jitter of ±1 ns.

II. LASER TRIGGERING

Laser triggering of a high-voltage (80-kV) spark gap [3] has demonstrated an overall jitter (±2σ) of ±200 ps. The spark gap is pressurized with SF_6, which has both a high DC dielectric strength and a relatively low ionization threshold for UV light, ~5×10^9 W/cm^2 at 3 atm. This is 3–4 times lower than the threshold for air at a pressure that would give similar voltage standoff. A UV laser beam is brought to a focus between the spark gap electrodes with sufficient intensity to ionize the SF_6, creating a plasma spark. The resulting distortion of the electric field in the gap triggers the switch (see Fig. 3).

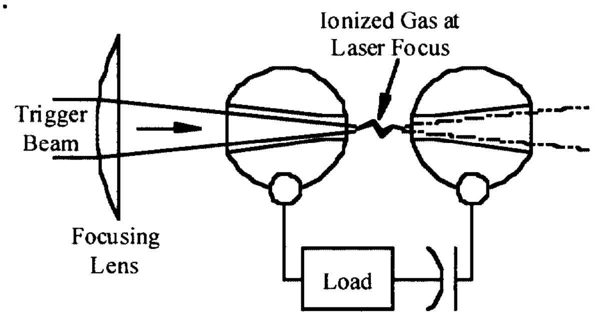

Figure 3. A laser-triggered spark gap.

The trigger laser used in the Nike system (see Fig. 4) is a commercially-available, Q-switched, frequency quadrupled Nd:YAG laser [4]. Only the UV output (266 nm) is used. The laser is rated at 50 mJ per pulse at 266 nm, with a pulse width of 5 ns FWHM and a full angle divergence of 600 μrads. The divergence is reduced to ~200 μrad by a 4:1 beam expander which gives a 2-cm diameter output beam. When focused by a lens of focal length f=20 cm, a 10 mJ pulse from this system will give an intensity of ~10^{11} W/cm^2, well above the ionization threshold for SF_6 at the pressures required for DC standoff in the mini-Marx. The laser pulse has an overall jitter of ±0.5 ns with respect to its external Q-switch trigger command.

Nike uses three laser-triggered mini-Marxes to fire all five of its 4-cm × 4-cm amplifiers. The amplifiers are fired at three different times, over a period of 80 ns. A 35–40 mJ pulse from the trigger laser is split into three beams of equal energy to trigger the three mini-Marxes. Path length differences between the trigger laser and each mini-Marx provide the required trigger timings. Two of the mini-Marxes have adjustable path lengths that allow changes of ±4 ns in trigger timing.

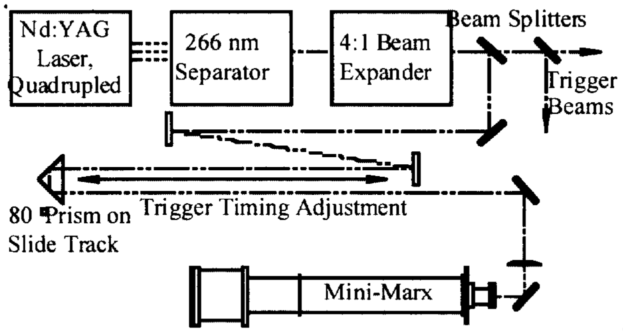

Figure 4. Simplified view of the optical system for laser triggering three mini-Marxes.

One characteristic of commercial Nd:YAG lasers must be taken into account in this application: thermal lensing of the laser rod. Commercial Nd:YAG lasers are typically designed to run at ~10-Hz repetition rates. The laser rod heats and expands during operation at these rep rates, with the center of the rod reaching a higher equilibrium temperature than its outer surface. Unequal expansion causes a distortion of the rod ends, so that they act as slightly convergent lenses. The optical cavity of a commercial Nd:YAG laser is designed to compensate for this thermal lensing, but this compensation is temperature (and hence rep rate) dependant. Typically, the compensation in a commercial laser is designed for continuous operation at or near its maximum rep rate.

The Nike laser is a single shot device, firing typically once an hour. Low-power laser alignment is done at ~0.3-Hz rep rates. Compensation for thermal lensing in the Nd:YAG trigger laser is optimized for low rep-rate operation by changing the curvature of the rear mirror in the optical cavity.

III. MINI-MARX MODIFICATIONS

The Veradyne mini-Marx is housed within a cylindrical pressure vessel with a cast, insulating liner (see Fig. 5). Access for a trigger laser beam is only practical through the ground plate at the low-voltage end of the assembly. A new first-stage spark gap and ground plate are required for laser triggering. The laser-triggered first-stage switch is rotated 90° relative to the original trigatron, allowing the trigger beam to enter perpendicularly through a fused silica window attached to the ground plate. The focusing lens and final steering mirror are external to the mini-Marx. The beam enters the anode-cathode gap of the switch along the center axis between the electrodes, via a small (1 mm) hole in the center of the ground electrode.

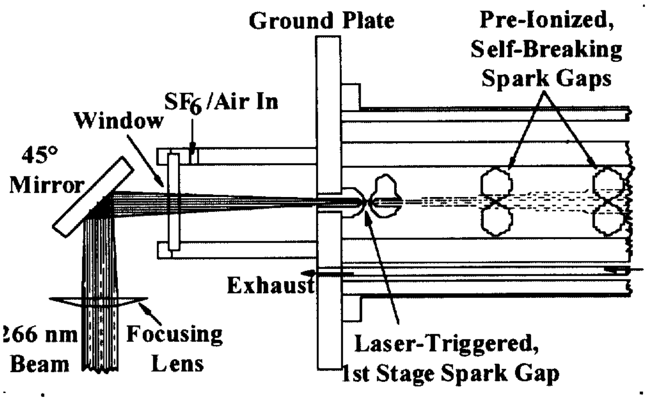

Figure 5. The Veradyne mini-Marx as modified for laser triggering.

In the original mini-Marx design, the switch electrodes are positioned so that UV irradiation from the closure of the first stage trigatron bathes the remaining, self-breaking gaps. UV pre-ionization of the switch electrodes allows more reliable erection of the Marx, with reduced jitter. The geometry of the laser-triggered first-stage switch, however, is such that the upper stage gaps are shielded from its UV flash at closure. To compensate for this, the trigger laser beam is provided with an exit as well as an entrance aperture in the first stage switch. After coming to a focus in the switch gap, the defocusing beam passes through the first-stage high-voltage electrode and directly illuminates the remaining gaps, pre-ionizing them.

IV. MINI-MARX OPERATION

The trigger laser provides enough intensity at each of its three foci to ionize air at 1 atm (see Fig. 6). This visible spark simplifies trigger laser alignment in the first stage switch. With the ground plate and attached mini-Marx firmly fastened to an optical table, the pressure vessel can be removed without disturbing the alignment. Coarse alignment is made with the pressure vessel open and pulled back about 10 cm from the ground plate, so that the first stage switch is visible. The beam path and focusing lens are adjusted so that the air spark falls in the middle of the anode-cathode gap. In addition, the defocusing beam is made to pass through the exit aperture in the high voltage electrode to illuminate the upper-stage spark gaps. Fine adjustment can be made to the trigger laser alignment while the pressure vessel is sealed, by observing the spark through the laser entrance window.

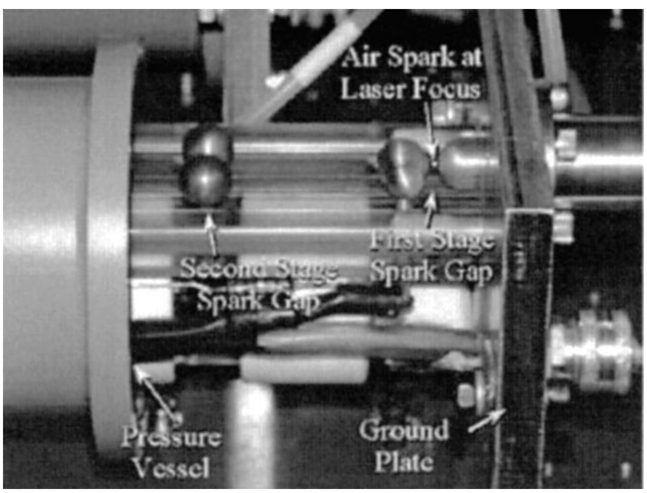

Figure 6. Photograph of the laser-triggered first-stage spark gap, showing the air spark at the laser focus.

A gas mixture containing SF_6, even in a modest proportion, retains much of the DC dielectric strength of the pure gas. To reduce the cost of operation, a mixture of 20% SF_6 and dry air is used in the Nike mini-Marxes. Operating pressure with this mixture is 2.7 atm absolute at a DC charge level of 30 kV. This is about 120% of the pressure at which the mini-Marx will begin to self-break. Gas flows through the mini-Marx at a low rate during operation, entering directly behind the laser entrance window in the ground plate and exhausting through a plastic scavenger tube that draws from the high-voltage end of the pressure vessel. This arrangement insures that fresh gas is circulated throughout the mini-Marx.

The electrical output from the mini-Marx to the trigger inputs of the 4-cm × 4-cm amplifier spark gaps is via 65-Ω coaxial cable, with three, 10-m long cables in parallel for each amplifier. This places a 22-Ω load on the mini-Marxes that trigger a single amplifier, and an 11-Ω load on those that trigger two amplifiers. Amplifier firing time jitter is the same in both cases.

V. EVALUATION

A laser-triggered mini-Marx system can provide fast-risetime, high-voltage, low-jitter trigger pulses for a variety of applications. Several mini-Marxes can be triggered by the same trigger laser pulse, reducing the relative jitter between them for a given shot. By adding inductive isolation in the DC charging cables, the Marxes can be electrically isolated from ground.

The mini-Marxes and the Q-switched, quadrupled Nd:YAG trigger-laser are commercially available. Modi fications required are slight; the additional mini-Marx parts can be fabricated at minimal cost, and the laser thermal-lensing compensation can typically be adjusted by a factory technician. The system is straightforward to operate and requires minimal maintenance.

An overlay of the output voltage for twenty shots of a laser-triggered mini-Marx is shown in Fig. 7. Voltage was measured with a capacitive voltmeter in one of the mini-Marx output cables. The jitter for these traces is 330 ps RMS at 50% of peak voltage. This gives an overall jitter ($\pm 2\sigma$) of ± 0.7 ns for the mini-Marx, with respect to the trigger-laser Q-switch fire command. Overall jitter for the Nike 4-cm × 4-cm amplifiers triggered by the mini-Marx is ± 1 ns.

As installed on Nike (see Fig. 8), the laser-triggered mini-Marx system permits more precise control of the 4-cm × 4-cm amplifiers. This has improved the Nike

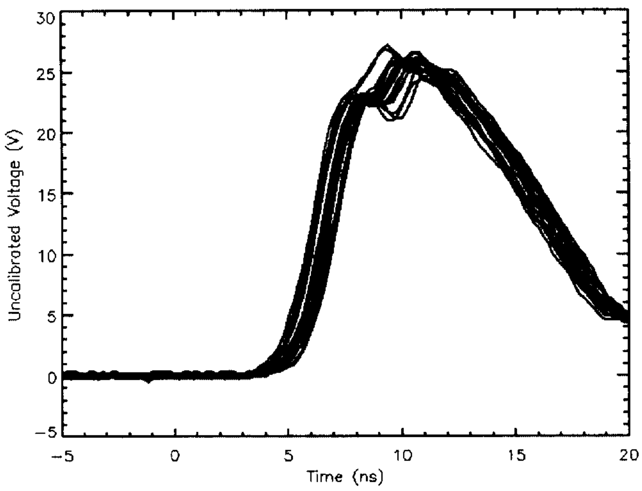

Figure 7. Laser-triggered mini-Marx output voltage versus time for twenty consecutive shots.

laser's pulse-shaping capabilities, making it a more versatile research instrument for inertial-confinement-fusion target studies.

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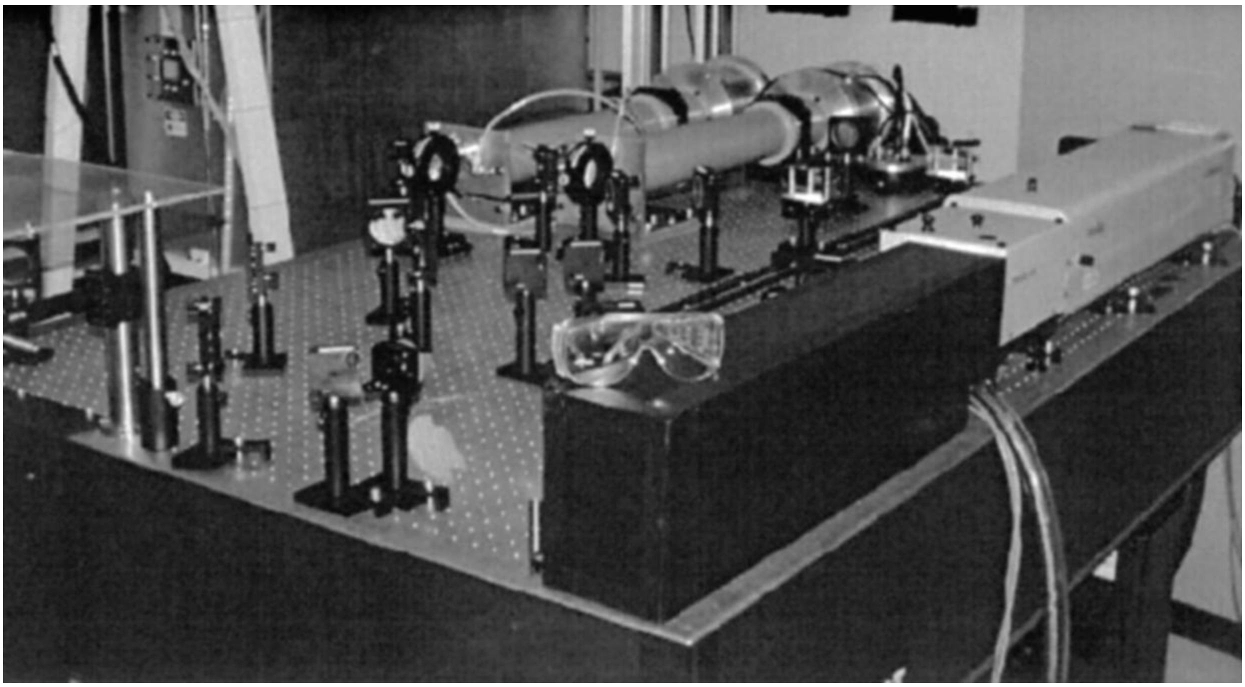

Figure 8. Photograph of the laser-triggered mini-Marx system, as installed on the Nike laser.